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The Hosts of Ultraluminous Infrared Galaxies

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Abstract. Complete samples of ultraluminous infrared galaxies (ULIGs[1]) have been imaged at R-band and K-band from Mauna Kea. Here we present a preliminary analysis of the host galaxy magnitudes and the 1-D radial profiles for a subset of objects in the *IRAS* 1-Jy sample of ULIGs ($z < 0.3$), and compare these properties with recently published data for "low-z" QSOs. ULIGs in the 1-Jy sample reside in luminous hosts, with mean luminosities $\sim 2.7\, L^*_{\rm K}$ ($\Delta_{\rm K} \sim 0.7$–$11\, L^*_{\rm K}$), and $\sim 2.2\, L^*_{\rm R}$ ($\Delta_{\rm R} \sim 0.5$–$9\, L^*_{\rm R}$), values which are remarkably similar in the mean and range for the hosts of low-z QSOs. Approximately one-third of ULIGs have single nuclei and radial profiles that are closely approximated by a $r^{1/4}$-law over the inner ~ 2–10 kpc radius. These "E-like" hosts have half-light radii, and surface brightness ($r_{1/2}$, $\mu_{1/2}$) similar to QSO hosts at R-band, but systematically smaller half-light radii than QSOs at K-band.

1. Introduction

ULIGs are an important class of extragalactic objects that appear to powered by a mixture of starburst and AGN activity, both of which are fueled by an enormous supply of molecular gas that has been funneled into the nuclear region during the merger of two gas-rich spirals. ULIGs rival quasi-stellar objects (QSOs) in bolometric luminosity, and there is speculation that ULIGs may indeed represent an important stage in the formation of QSOs as well as powerful

[1] $L_{\rm ir} \equiv L(8 - 1000\, \mu m) > 10^{12}\, L_\odot$; unless otherwise stated, $H_{\rm o} = 75\, {\rm km\, s^{-1}\, Mpc^{-1}}$, $q_{\rm o} = 0$

radio galaxies, and that they may also represent a primary stage in the formation of giant ellipticals (see Sanders & Mirabel 1996 for a more complete review).

A complete sample of 115 ULIGs ($f_{60} > 1$ Jy) was compiled by Kim (1995; see also Kim & Sanders 1998) from redshift surveys of objects in the *IRAS* Faint Source Catalog (FSC: Moshir et al. 1992). As the nearest and brightest ULIGs, the "1-Jy sample" provides the best list of objects for detailed multiwavelength studies. Optical spectroscopy for the entire sample has recently been published by Veilleux, Kim, & Sanders (1999), and near-IR spectra have been published for 60% of the total sample by Veilleux, Sanders, & Kim (1999). High-resolution, tip-tilt, optical and near-IR images have just recently been obtained for the entire sample and these data are currently being reduced.

Here we present further analysis of the original data from Kim (1995) in order to highlight the first intriguing results from a comparison of the host galaxy properties of ULIGs with recently published data on the hosts of QSOs.

2. Imaging Observations – The IRAS 1-Jy Sample

Photometric CCD images of a subset of the 115 ULIGs in the IRAS 1-Jy sample were originally obtained at K-band[2] (37/115) and R-band (83/115) using the QUIRC 256×256 infrared camera (Hodapp, Rayner, & Irwin 1992) and Tek 2048×2048 optical CCD camera, respectively on the University of Hawaii (UH) 2.2m telescope on Mauna Kea. Details of the observations, data reduction, and photometry can be found in Kim (1995).

3. Host Galaxies of ULIGs

One of the basic properties of ULIGs, and perhaps the most straightforward to measure, is the total magnitude of the host galaxy and any point-like nuclear source that may be present. Kim (1995) found that the mean total magnitudes of ULIGs in the 1-Jy sample were $\sim 3\,L^*_{\rm K}$ and $\sim 2.7\,L^*_{\rm R}$, with a sample range of a factor of $\sim 3^{\pm 1}$ in both bands. These mean values are similar to the magnitudes of giant ellipticals (gEs) and brightest cluster galaxies (BCGs).

Kim (1995) classified $\sim 1/3$ of the R-band images of ULIGs as elliptical-like based on a reasonable $r^{1/4}$-law fit to the radial surface brightness profile over a relatively large range of host galaxy radius, typically $\Delta r = 2$–10 kpc. An example of these "E-like" ULIGs is IRAS 05189-2524 shown in Figure 1. A majority of these objects have Seyfert 1 optical or near-IR spectra, (similar to the recent results reported by Zheng et al. 1999), hence the apt description of these "E-like" ULIGs as "infrared QSOs". An additional $\sim 1/3$ of the R-band images were classified as "E/Sp" to describe the fact that an $r^{1/4}$ law was a better fit than an exponential-disk model over a large range of galactocentric radius. The remaining $\sim 1/3$ of the 1-Jy ULIGs were divided between a few spiral-like hosts (i.e. good exponential fit), highly distorted "Amorphous" hosts (typically closely spaced double nuclei where exponential-law and $r^{1/4}$-law descriptions

[2] Kim (1995) observed objects using a K′ filter. These data have been converted to the standard K-band using the small correction terms given in Wainscoat & Cowie (1992)

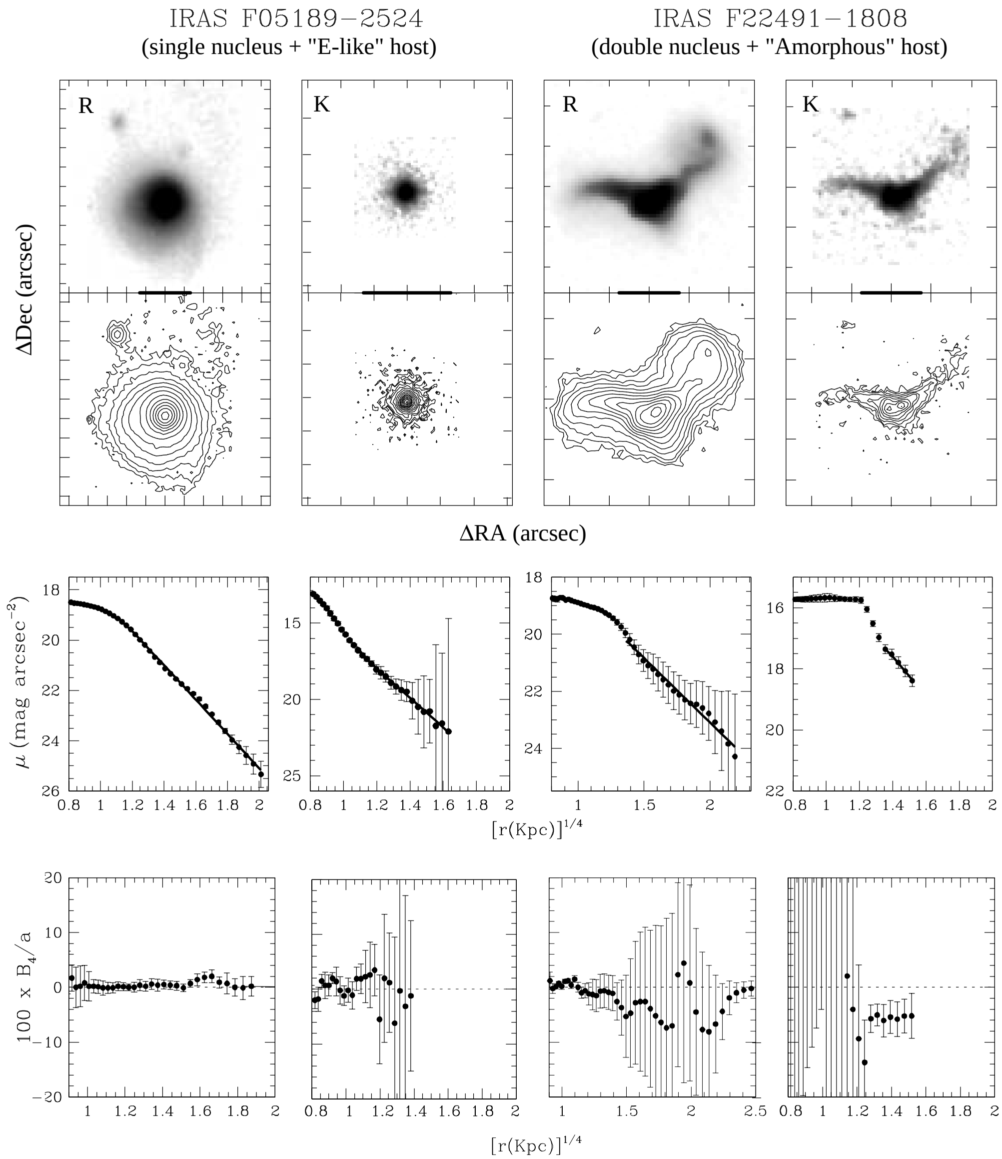

Figure 1. R-band and K-band images and 1-D surface intensity profiles for two ULIGs – the “IR-QSO” IRAS F05189−2524 and the “cool” ULIG IRAS 22491−1808. Rows 1 and 2 show the UH 2.2m tip-tilt images in grayscale and contour form respectively. North is to the top, east is to the left, tick marks are at 10″ intervals, and the solid bar represents 10 kpc. Rows 3 and 4 show the 1-D radial variation of surface brightness and the parameter B_4/a as a function of $r^{1/4}$. The best $r^{1/4}$ fit to the surface brightness profile (excluding the central 1.5″ radius of the image) is given by the straight line.

were equally bad fits; IRAS 22491-1808 in Figure 1 is a good example), and a few objects with largely non-overlapping disks where a single-host picture was clearly inappropriate.

In comparing the R-band and K-band radial profiles of the ULIGs, there were both widespread differences as well as similarities. For example, in the complete sample strong point-like nuclei at R-band are relatively rare; the fraction of the total R-band light within the inner 2 kpc radius is typically $< 20\%$. However, the K-band surface brightness profiles are nearly always more centrally peaked, (e.g. IRAS 05189-2524; see Figure 1). As for the hosts, the distribution of host types ("E-like", "E/Sp", etc.) was generally the same at K-band as that found at R-band with the only caveat being that the moderate depth of the K-band images meant that the galactocentric radius of the outermost measured K-band contour was typically $\sim 2/3$ that of the outer R-band contour.

4. Properties of "E-like" ULIG Hosts

Figure 2 shows the distribution of host galaxy magnitudes for the subsample of "single-nucleus" objects in the IRAS 1-Jy sample, their R$-$K colors and the half-light radii and surface brightness ($r_{1/2}$, $\mu_{1/2}$) derived from an $r^{1/4}$-law fit to the 1-D radial brightness profiles. This analysis is similar to the analysis carried out by Kim (1995), except here we have subtracted off any obvious nuclear point source that may be present in the images of the 1-Jy ULIGs. An immediate result is that nearly all ULIGs reside in hosts with luminosities above L^*. The mean host luminosities are $2.7\,L^*_K$ and $2.2\,L^*_R$. The radial surface brightness profiles over the range $\Delta r \sim 2$–10 kpc are well-fit by a deVaucouleurs $r^{1/4}$-law, whereas the light distribution in the inner few kpc is more schizophrenic, most likely due to both heavy dust obscuration as well as a recent luminous starburst. Given these observations, and the reasonable assumption from continuity arguments that the non "E-like" ULIGs will soon resemble their slightly more evolved "E-like" cousins, it would appear that ULIGs in general reside in luminous hosts that are similar in many ways to gEs and BCGs.

4.1. Comparison with QSOs

One of the most interesting new results from the current study of "E-like" ULIGs is that their mean luminosities at R- and K-band are *nearly identical* to that found previously for the hosts of QSOs (e.g. McLeod & Rieke 1994, 1995; Disney et al. 1995; Boyce et al. 1996; Taylor et al. 1996; Sanders & Surace 1997; Hutchings 1997; Bahcall et al. 1997; Surace 1998; McLure et al. 1999). As shown in Figure 2, even the range of luminosities for ULIG hosts appears similar to the range observed for QSO hosts, typically 1–10 L^* at both K-band (Taylor et al. 1996) and R-band (McLure et al. 1999). The range of R$-$K color of the hosts of ULIGs and QSOs are similar (typically 2.5–3.5 mag), with the exception of a few red ULIGs with R$-$K$\,>4$ mag. However, the radial surface brightness distributions clearly show systematic differences, with the half-light radii at R-band and K-band for ULIGs being as much as a factor of 2.5 and 3.5 less respectively than found for the hosts of QSOs. Thus despite the overall similarity in host total magnitudes, there is clearly an excess of emission in the inner disks of IR-selected ULIGs as compared with optically-selected QSOs.

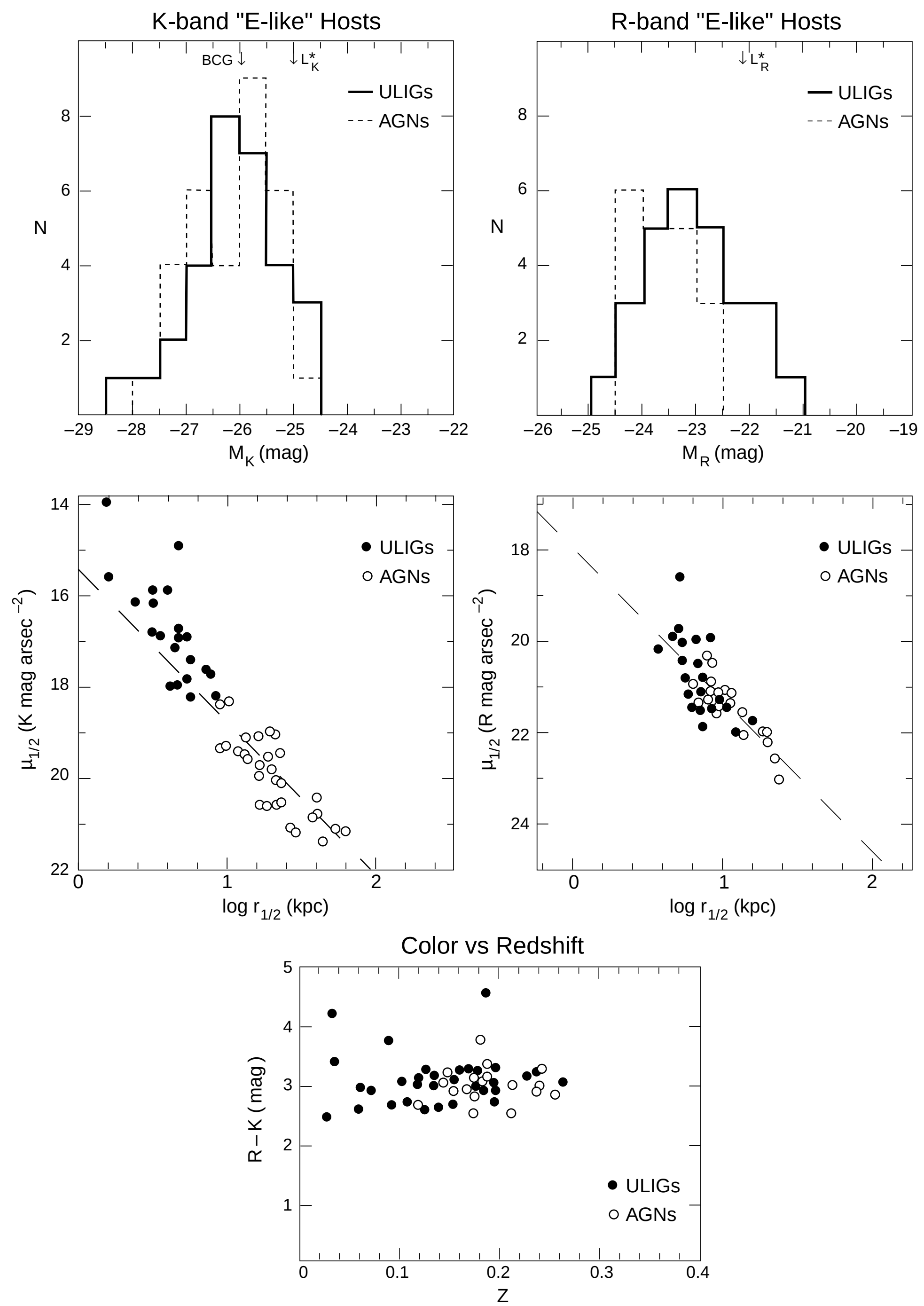

Figure 2. *[Note: For comparison with QSO data, all ULIG measured parameters have been converted to $H_o = 75\ km\,s^{-1} Mpc^{-1}$, $q_o = 0$.]* R-band and K-band magnitudes, effective radii and surface brightness ($r_{1/2}$, $\mu_{1/2}$), and (R−K) colors for the hosts of those ULIGs with single nuclei and $r^{1/4}$-like radial profiles ("E-like"), compared with recently published K-band and R-band data for the hosts of AGNs. [Here we use AGNs to refer to the composite K-band and R-band samples of "low-z" objects (i.e. RLQs+RQQs+RGs) as defined by Taylor et al. (1996) and McLure et al. (1999), respectively.]

5. Conclusions

ULIGs in the local Universe ($z < 0.3$) reside in luminous hosts with mean luminosities ~ 2–$3\,L^*$ at R- and K-band. Continuity arguments suggest that ULIG hosts are evolving into giant ellipticals. The properties of ULIGs which already have "E-like" hosts are quite similar to those of QSOs, but with an excess of emission at K-band in the inner several kpc radius, perhaps due to a population of red giants from an aging powerful circumnuclear starburst. These results lend further support to the hypothesis that ULIGs may be the infrared precursors to optically-selected QSOs.

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References

Bahcall, J.N., Kirhakos, S., Saxe, D.H., & Schneider, D.P. 1997, ApJ, 479, 642

Boyce, P.J., et al. 1996, ApJ, 473, 760

Disney, M.J., et al. 1995, Nature, 376, 150

Dunlop, J., Taylor, G., Hughes, D., & Robson, E. 1993, MNRAS, 264, 455

Hodapp, K.-W., Rayner, J., & Irwin, E. 1992, PASP, 104, 441

Hutchings, J.B. 1997, in Quasar Hosts, eds. D.L. Clements & I. Perez-Fournon (Berlin: Springer), 45

Kim, D.-C. 1995, PhD Thesis, University of Hawaii

Kim, D.-C. & Sanders, D. B. 1998, ApJS, 119, 41

McLeod, K.K., & Rieke, GH. 1994, ApJ, 431, 137

McLeod, K.K., & Rieke, G.H. 1995, ApJ, 454, L77

McLure, R.J., Dunlop, J.S., Kukula, M.J., Baum, S.A., O'Dea, C.P., & Hughes, D.H. 1999, ApJ, in press (astro-ph/9809030)

Moshir, M. et al. 1992, Explanatory Supplement to the IRAS Faint Source Survey, Version 2, JPL D-10015 8/92, Pasadena: JPL

Sanders, D.B., & Mirabel, I.F. 1996, ARA&A, 34, 749

Sanders, D.B., & Surace, J.A. 1997, in Quasar Hosts, eds. D.L. Clements & I. Perez-Fournon (Berlin: Springer), 229

Surace, J.A. 1998, PhD Thesis, University of Hawaii

Taylor, G., Dunlop, J., Hughes, D., & Robson, E. 1996, MNRAS, 283, 930

Veilleux, S., Kim, D.-C., & Sanders, D.B. 1999, ApJ, 522, 113

Veilleux, S., Sanders, D.B., & Kim, D.-C. 1999, ApJ, 522, 139

Wainscoat, R.J., & Cowie, L.L. 1992, AJ, 412, 535

Zheng, Z., Wu, H., Mao, S., Xia, X.-Y., Deng, Z.-G., & Zou, Z.-L. 1999, A&A, 349, 735